Recurring ^{3}He-rich Solar Energetic Particle Events

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Abstract: Using the SIT instrument aboard STEREO we have examined the abundance of the ^{3}He during the ascending phase of solar cycle 24 from January 2010 through December 2012. We report on several cases when ^{3}He-rich solar energetic particle events were successively observed on ACE and STEREO-A with delays consistent with the Carrington rotation rate. In the investigated period ACE and STEREO-A were significantly separated in the heliolongitude corresponding to the solar rotation times from 5 to 10 days. We inspect STEREO-A EUV images and use the potential-field source-surface extrapolations together with in-situ magnetic field data to identify responsible solar sources. We find the ^{3}He/^{4}He ratio highly variable in these events and correlated between the spacecraft for the cases with the same connection region on the Sun.

Keywords: solar energetic particles, flares, abundances, PFSS.

1 Introduction

^{3}He-rich solar energetic particle (SEP) events are characterized by huge enhancements of the rare isotope ^{3}He over solar system abundances. The enrichment of the ^{3}He is believed to be caused by selective heating mechanisms due to its unique charge to mass ratio (see e.g., review by [1]). Recently the sources of such events have been investigated with help of imaging observations [2, 3]. The sources were small flares located near open field region and showed tendency to recur [3].

There were reported a few simultaneous ^{3}He-rich SEP events [4, 5] observed on spatially separated spacecraft (s/c). Multi-spacecraft observations of successive events have not been systematically investigated. In the present paper, we examine ^{3}He-rich SEP events successively observed on two s/c widely separated in heliolongitude and identify cases where they are connected to the same solar active region. We use observations from ACE and STEREO-A (STA) s/c which had separation between 65° and 130° during the study period (January 2010-December 2012).

2 Observations

Energetic ^{3}He observations used in this paper are from time-of-flight mass spectrometers SIT [6] on STA and ULEIS [7] on ACE. The STA s/c is in a heliocentric orbit at $\sim$1 AU near the ecliptic plane increasing its separation from Earth at a rate of $\sim$22°/year. The ACE s/c is in an orbit around the L1 point. Since SIT is less sensitive to small ^{3}He-rich SEP events than ULEIS we identified events on STA first and then we search for the corresponding events on ACE.

In the survey period there were 32 STA ^{3}He-rich events found in the energy range $0.2-0.5$ MeV/n (8 events in 2010; 12 in 2011 and 12 in 2012). In 19 cases a ^{3}He-rich event was observed at same energy earlier by ACE with the start time within $\pm$2 days of corotation delay between the two s/c. A common connection solar region was found in 12 cases, which are listed in Table 1.

Columns (2)-(3) of Table 1 show start times of ACE and STA ^{3}He-rich SEP events. The approximate start times were determined from the increase of number of pulse-height data points above the ^{3}He background inspecting the ULEIS/SIT He mass spectrograms. The 385 keV/n ^{3}He/^{4}He event-averaged ratios on ACE and STA are in columns (4) and (5), respectively. The STA ^{3}He/^{4}He ratios were corrected for spillover of the ^{4}He to ^{3}He [8]. Four STA events with ^{3}He/^{4}He $>$1 were in our earlier study [8]. Columns (6)-(7) list the Fe/O ratios and columns (8)-(9) the ^{3}He fluences for ACE and STA, respectively. Column (10) lists ACE and STA s/c common connection regions on the Sun. The numbers refer to NOAA active regions (AR). According to daily Solar Region Summary, all but two of them (1197, 1461) were regions with sunspots. Sometimes two ^{3}He events coming from the same AR were observed by one s/c. ACE November 14 and 17, 2010 events were associated with AR 1124. These two events show quite different (factor of $\sim$14) ^{3}He/^{4}He ratios. Further examples are STA October 21 and 24, 2010 events associated with AR 1112.

Figure 1 shows photospheric magnetic field maps with potential-field source-surface (PFSS) model field lines at the start times of the ACE events. The field lines shown are those which are open to the heliosphere for the range of s/c heliolatitudes. This magnetic field model is based on SOHO/SDO magnetogram data [9] and it is available via SolarSoft with 6-hour cadence. Blue/purple diamonds mark footpoints of the Earth/STA at the source surface at 2.5R$_\odot$ from Sun center. Outside the source surface we assume the field is radial and has a form of Parker spiral. The footpoint longitudes were determined from Parker angle using the measured solar wind speed with SWEPAM/ACE and PLASTIC/STA instruments. Yellow circles are source regions on the Sun listed in Table 1. These were identified by examining the locations of the s/c footpoint during the ^{3}He-rich periods. The technique which combines Parker spiral for the interplanetary space and PFSS model for the corona has been used in identification of sources in the ^{3}He-rich SEP events (e.g., [2]). In addition to this approach we also check whether the in-situ magnetic field po-

Year	Start time		$^3He/^4He$ [a]		Fe/O [a]		^{3}He Fluence [a] (x10^3)		AR
	ACE	STA	ACE	STA	ACE	STA	ACE	STA	
2010	Jan 27.3	Feb 2.8	0.13±0.02	0.29±0.04	0.58±0.10	0.57±0.21	5.72±0.83	7.78±0.91	1041
2010	Feb 8.7 [b]	Feb 14.3	0.21±0.02	0.54±0.05	0.89±0.16	1.50±0.34	21.5±1.6	16.0±1.3	1045
2010	Oct 17.9	Oct 21.4	0.46±0.04	1.12±0.24	1.27±0.23	2.25±1.35	21.0±1.6	4.48±0.69	1112
2010	Oct 17.9	Oct 24.6	0.46±0.04	0.16±0.03	1.27±0.23	1.17±0.65	21.0±1.6	3.52±0.61	1112
2010	Nov 14.6	Nov 22.4	0.20±0.02	1.24±0.16	1.20±0.18	1.00±0.43	26.3±1.8	13.8±1.2	1124
2010	Nov 17.7	Nov 22.4	2.75±0.33	1.24±0.16	1.25±0.34	1.00±0.43	32.8±2.0	13.8±1.2	1124
2011	Jan 27.9	Feb 1.8	0.08±0.01	0.09±0.02	1.15±0.18	4.67±2.97	10.7±1.1	1.71±0.43	1149
2011	Apr 29.8	May 6.4	0.02±0.01	3.90±0.62	...	1.43±0.70	0.95±0.34	18.5±1.4	1197
2011	Jul 9.0	Jul 16.5	2.35±0.13	3.28±0.20	1.31±0.20	1.13±0.28	127±4	105±3	1246
2012	Jan 7.3	Jan 16.0	1.33±0.26	0.82±0.22	...	1.67±1.22	7.15±0.92	2.45±0.51	1392
2012	Apr 24.9	May 2.0	0.11±0.01	0.05±0.01	0.99±0.11	0.97±0.18	23.4±1.7	7.36±0.89	1461
2012	Nov 20.5	Nov 30.9	6.72±0.52	0.80±0.27	0.89±0.16	...	154±4	1.60±0.41	1613

[a] 320–450 keV/n; fluence units - particles (cm^2 sr MeV/n)$^{-1}$

[b] event discussed in [5]

Table 1: Recurring ^{3}He-rich SEP events consecutively detected by ULEIS/ACE and SIT/STEREO-A.

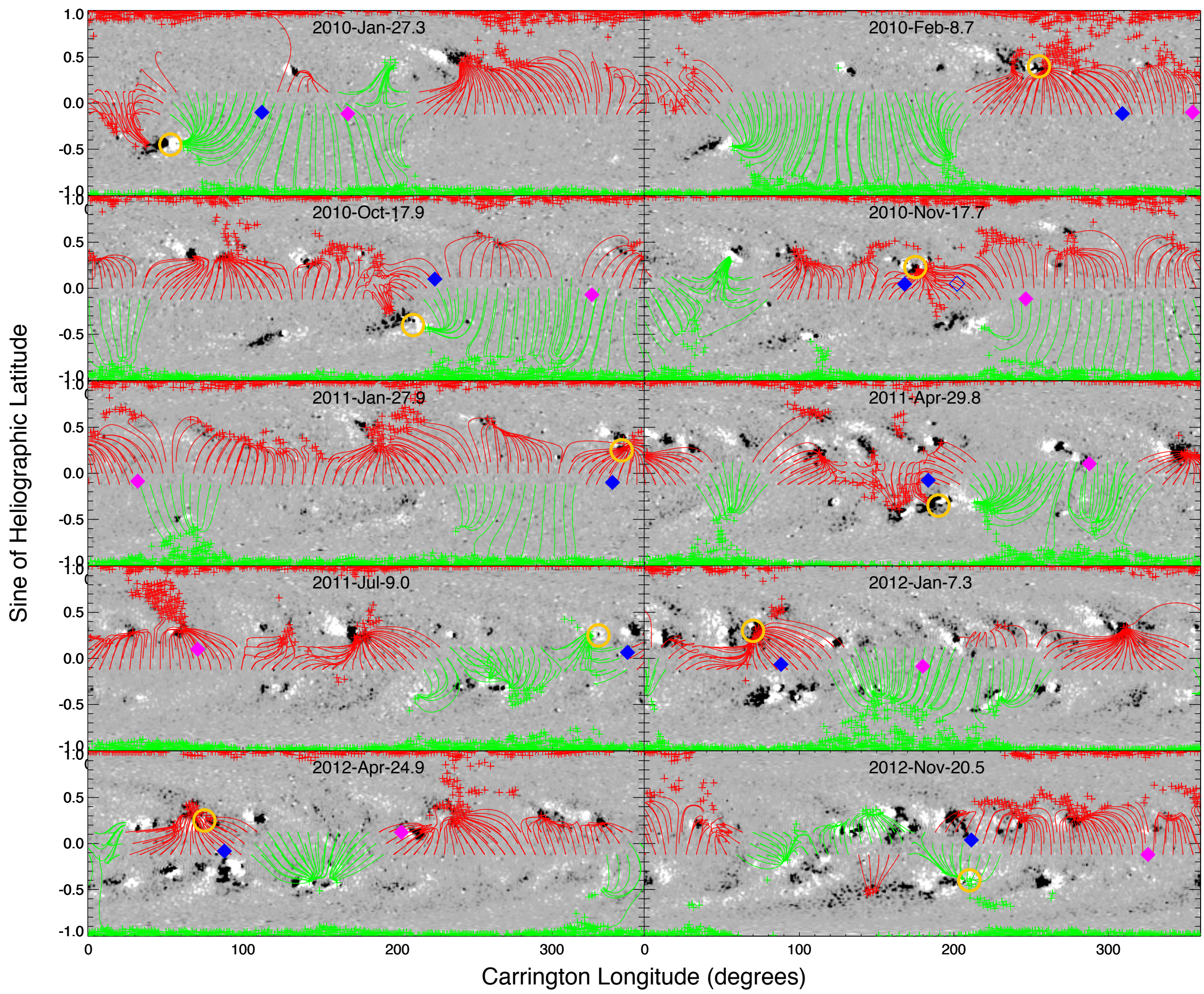

Figure 1: Photospheric magnetic field with PFSS model coronal field lines at the start times of the ACE events. Shown are field lines which intersect source surface at latitudes 0° and ±7°. Red/green indicates negative/positive open field. Blue/purple diamonds mark Earth/STA footpoints on the source surface for event start times on ACE. Yellow circles mark the ACE s/c connection locations on the Sun. The open diamond in panel 2010-Nov-17.7 indicates Earth(ACE) position on 2010-Nov-14.6. Note that during the events the s/c footpoint moves several degrees toward the left.

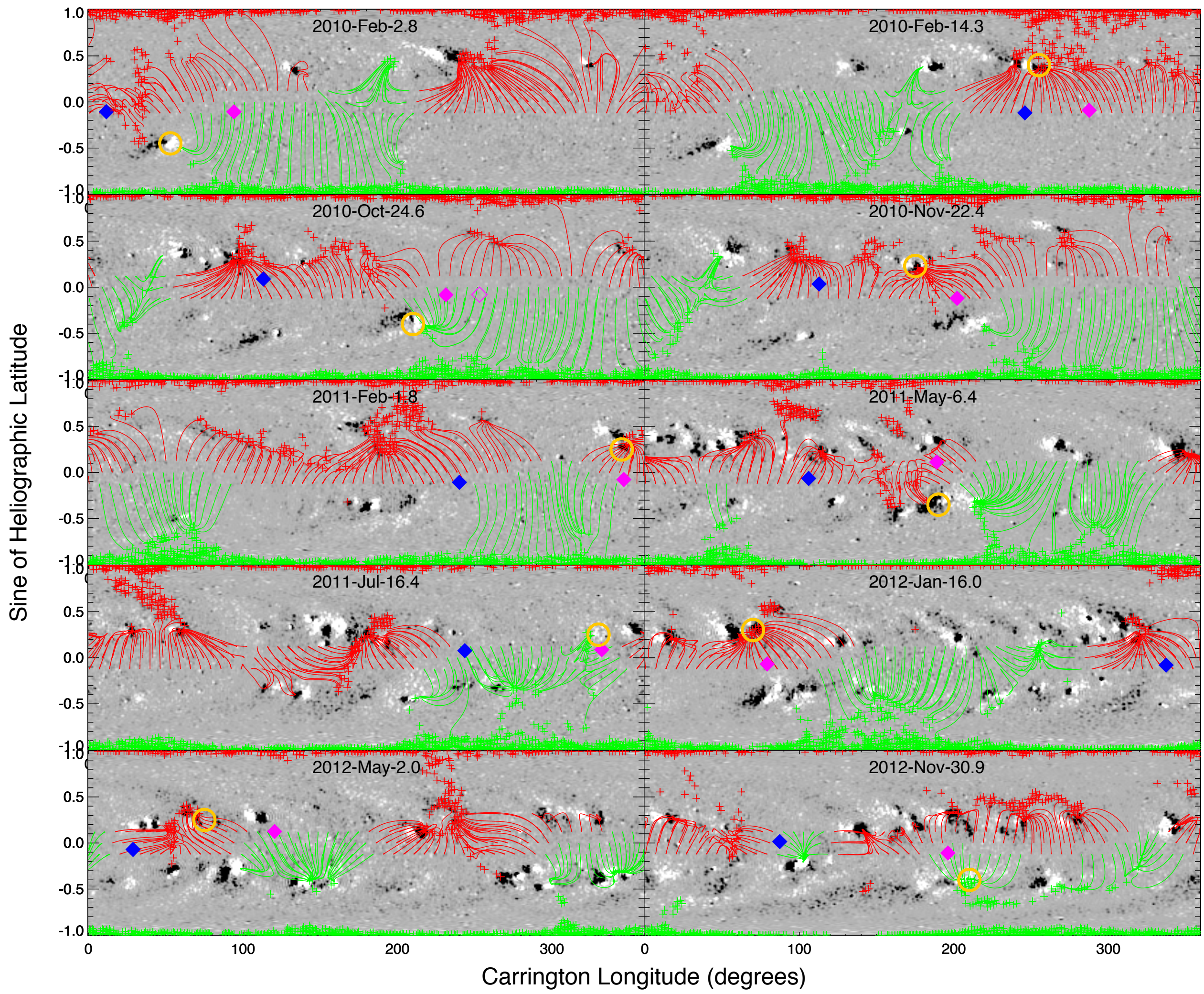

Figure 2: Same as Fig. 1 but for STA events start times. Open diamond in panel 2010-Oct-24.6 indicates STA position on 2010-Oct-21.4. Yellow circles mark the STA s/c connection locations on the Sun.

larity matches the polarity from PFSS extrapolations. For this purpose we use 1-hour data from MAG instruments on ACE and STA.

Figure 2 is similar to Fig. 1 but magnetic field and s/c footpoints are for STA events start times. We note that PFSS coronal model field lines are less accurate for STA events. The STA western solar hemisphere was not facing the Earth during the investigated period and thus not visible by SOHO or SDO s/c. Notice on May 2, 2012 event where PFSS model suggests connection via positive (green) polarity field while in-situ polarity (not shown) changes sign from positive to negative at the beginning of the event. The marked AR provides negative polarity field lines to the distance of $\sim$15° from the STA footpoint. Offsets of 10° due to limitations of the PFSS model and simple Parker spiral with constant solar wind speeds have been previously reported [2].

Further we examine if the identified connection regions were flaring before the event. For ACE we used NOAA Solar Event Reports (http://www.swpc.noaa.gov) and for STA used SECCHI EUV observations. We searched for X-ray flares or EUV brightening in 5-8 hour interval before the event start time. The length of this interval roughly corresponds to the travel time of 0.2-0.5 MeV/n ions along the spiral with length of 1.1 AU. Using the NOAA list we found X-ray flares (B or C class) in the connected regions for 5 out of 11 ACE ^{3}He-rich SEP events in Table 1 (Feb 8, Oct 17, Nov 14, 2010; Jan 27, 2011; Jan 7, 2012). For rest of the ACE events the SECCHI/STA EUV 195 Å images show clear brightening in the connected regions. Note that in the STA view the ARs for ACE events were seen near the eastern solar limb. The same solar source for February 8, 2010 ACE event has been reported by another study [5]. During this event, ^{3}He was simultaneously observed by the two STEREO s/c but without known source.

We examined full resolution SECCHI images with 5-minute cadence also for STA events. The ARs associated with Oct 21, 24; Nov 22, 2010; and Nov 30, 2012 events showed clear brightening in EUV images. Significant activity with expanding and collapsing loops was seen in the AR associated with Feb 1, 2011 event and with material ejections in AR for Feb 14, 2010 event. Only minor brightening was seen in ARs marked for the Feb 2, 2010; May 6, 2011 and Jan 16, 2012 events. Small AR 1246 at the border of the coronal hole, associated with ACE Jul 09, 2011 event, was very faint on July 16, 2011. SECCHI images showed two new regions, one emerging on the east side and other on the west side of the coronal hole. The

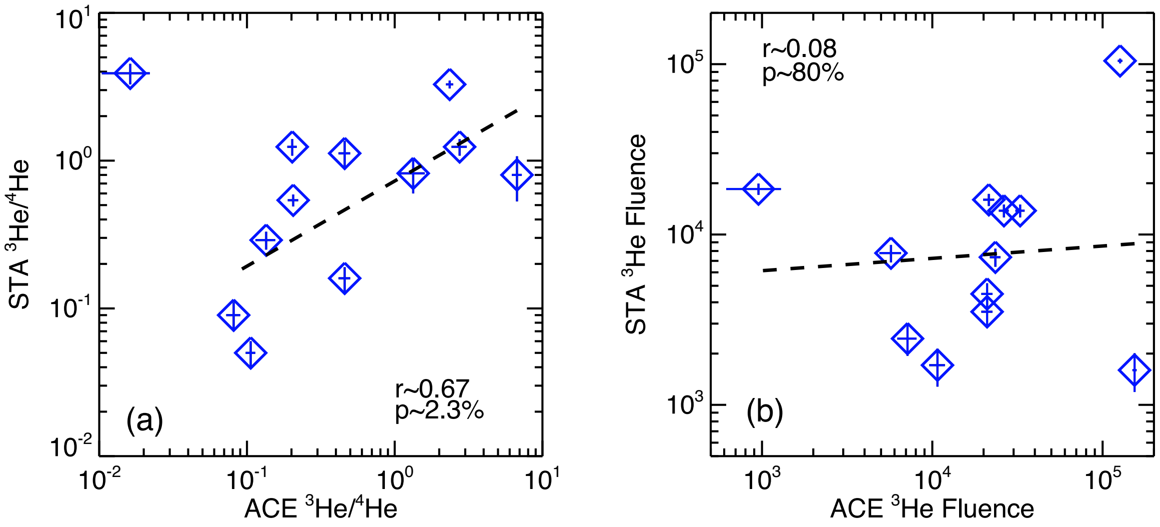

Figure 3: (a) ULEIS/ACE ^{3}He/^{4}He ratio vs. SIT/STEREO-A ^{3}He/^{4}He ratio for 320-450 keV/n for events in Table 1. (b) ULEIS/ACE ^{3}He fluence (particles/cm^2 sr MeV/n) vs. SIT/STEREO-A ^{3}He fluence for 320-450 keV/n. The dashed lines are power-law fit. The quantities r and p denote the correlation coefficient and its statistical significance.

later one showed only little activity. ^{3}He source for May 2, 2012 event is less clear. The marked AR showed no obvious brightening but the AR on the south with open to ecliptic positive field lines was highly active with material ejections.

Figure 3a shows scatter plot of 320-450 keV/n ^{3}He/^{4}He ratios on ACE and STA for events in Table 1. If we exclude the outlier point in upper left corner of the plot (April/May 2011 events) the ^{3}He/^{4}He ratio shows significant positive correlation (0.67) between the two spacecraft with low probability of being from random population ($< 3\%$). This means that the ^{3}He enrichment did not change much after $\sim$5-10 days of corotation in different events associated with the same AR. However, other studies have shown that the ^{3}He/^{4}He ratio changes significantly from one event to the next event in the same active region [3]. This figure also shows large event to event variations in the ^{3}He/^{4}He ratio spanning about two orders of magnitude. Figure 3b shows scatter plot of 320-450 keV/n ^{3}He fluences on ACE and STA for events in Table 1. The ^{3}He fluences are not correlated even if we exclude the outlier point in lower right corner (November 2012 events).

3 Summary

In the investigated period we have identified several ^{3}He-rich events successively observed on ACE and STEREO-A when the two s/c were connected to the same solar region. Although the sunspot number was lower in 2010 than in 2012, more common sources were found in 2010, when s/c were less separated, than in 2012, when separation between the s/c markedly increased. This could be either because of decease of the flaring in the AR or vanishing of the open ecliptic field lines during the corotation time. Anyway, identifying the events when the s/c are more separated could set up an upper limit on how long a single source may provide energetic ^{3}He ions.

We found that ^{3}He abundance in the events associated with the same AR does not show significant temporal changes, although other studies have not shown this. The largest difference (factor of $\sim$200) between ^{3}He enrichments was seen for ACE Apr 29, 2011 and STA May 6, 2011 events. This is also the case when the open field lines (of the same polarity) from several ARs were in close proximity to the s/c footpoint. Another larger differences (factor of 6 and 8) were found for ACE Nov 14, 2010 and STA Nov 22, 2010 events and for ACE Nov 20, 2012 and STA Nov 30, 2012 events. We note that at the beginning of ACE Nov 14, 2010 event there were open ecliptic lines also from the southern hemisphere AR (not shown in Fig. 1). Thus the cases with the marked differences are those when multiple sources might contribute with the ^{3}He.

The long lasting sources of energetic ^{3}He identified in this paper tend to be regions with sunspots. It is not clear how different types/intensities of the flaring seen in these regions are related to the large event to event variability in the ^{3}He enrichment.

Acknowledgment: This work was supported by the Bundesministerium für Wirtschaft under grant 50 OC 0904. The work at JHU/APL was supported by NASA under contract SA4889-26309 from the University of California Berkeley. We thank the ACE SWEPAM/MAG and the STEREO PLASTIC instrument teams for the use of the solar wind plasma data.

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